

# A new look at Anomalous X-ray pulsars

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**Abstract.** We explore a possibility to explain the phenomenon of the Anomalous X-ray Pulsars (AXP) and Soft Gamma-ray Repeaters (SGR) within the scenario of fall-back magnetic accretion onto a young isolated neutron star. The X-ray emission of the pulsar in this case is originated due to accretion of matter onto the surface of the neutron star from the magnetic slab surrounding its magnetosphere. The expected spin-down rate of the neutron star within this approach is close to the observed value. We show that these neutron stars are relatively young and are going through a transition from the propeller state to the accretor state. The pulsars activity in the gamma-rays is connected with their relative youth and is provided by the energy stored in the non-equilibrium layer located in the crust of low-mass neutron stars. This energy can be released due to mixing of matter in the neutron star crust with super heavy nuclei approaching its surface and getting unstable. The nuclei fission in the low-density region initiates chain reactions leading to the nuclear explosion. The outbursts are likely to be triggered by an instability developing in the region where the matter accreted by the neutron star is accumulated at the magnetic pole regions.

**Keywords:** Accretion and accretion disks, X-ray binaries, neutron star, pulsars, magnetic field, anomalous X-ray pulsars, Soft gamma-ray repeaters

**PACS:** 97.10.Gz, 97.80.Jp, 95.30.Qd

## 1. INTRODUCTION

Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) constitute a subclass of X-ray sources with regular pulsations in their X-ray emission. One of the main features which allows to distinguish them among other X-ray pulsars is that all of them are isolated objects. None of the presently known 12 AXPs and 11 SGRs is a member of a close binary system [1]. Persistent pulsations with the period  $P_s$  ranging from 2 to 12 seconds and increasing with an average rate  $\dot{\nu} \sim 10^{-11} - 10^{-14} \text{ Hz s}^{-1}$ , can be easily explained within the model of a compact star with non-uniform temperature distribution over its surface and the spin frequency  $\nu = 1/P_s$ . Relatively small value of the spin period as well as soft X-ray spectrum and optical identification of some of these pulsars with supernova remnants leave little doubt that AXPs and SGRs are isolated neutron stars [2, 3, 4, 5].

Most known so far isolated neutron stars belong to a subclass of radio-pulsars. Similar to AXPs and SGRs, these stars are in the spin-down state and some of them are the sources of pulsating X-ray emission. However, the similarity between the radio-pulsars

and the objects from the subclass of AXPs and SGRs ends here. The X-ray luminosity of AXPs and SGRs,  $L_X \sim 10^{33} - 10^{35} \text{ erg s}^{-1}$ , significantly exceeds the spin-down rate of these neutron stars. Moreover, the unique signature of this subclass of X-ray pulsars is recurrent gamma-ray outbursts during which the energy of  $\sim 10^{40} - 10^{42} \text{ erg}$  is released on the timescale of one to several seconds [6, 7], as well as giant gamma-ray bursts observed from SGRs and characterized by the energy release of  $10^{43} - 10^{46} \text{ erg}$  during fractions of a second [8]. The pulsar luminosity during these events significantly exceeds the Eddington limit which eliminates a possibility to explain gamma-ray bursts in the terms of any accretion model. Finally, the spin periods of AXPs and SGRs range in a narrow interval between 2 and 12 seconds that essentially differentiates them from both ejecting and accreting pulsars whose periods lay in the vast interval covering six orders of magnitude (from 1.5 ms to tens of thousands seconds).

Two most popular approaches can be distinguished among numerous attempts of modelling AXPs and SGRs. The first one exclusively associates the uniqueness of these objects with peculiar qualities of the neutron star itself, while the influence of environment on its evolution and generation of high-energy radiation is assumed to be insignificant. The most popular within this approach is a hypothesis about so called magnetars which considers AXPs and SGRs as a subclass of radio-pulsars endowed with surface dipole magnetic field as high as  $10^{14} - 10^{15} \text{ G}$ . Under this assumption the spin-down rate of a neutron star due to magneto-dipole emission is in a good agreement with observed value, and generation of high-energy emission from the pulsar is described in terms of decay and flaring dissipation of its strong magnetic field [9, 10].

It is worth mentioning, however, that magnetic field is not the only possible energy source for the flaring activity of neutron stars. As shown in [11, 12, 13], a non-equilibrium layer consisting of super-heavy nuclei is formed in the interior of the neutron star during the stage of its rapid cooling. This layer, located at the bottom of the upper crust of the star, is in a static equilibrium at the densities  $10^{10} - 10^{12} \text{ g cm}^{-3}$ . The nuclear energy stored in the layer of the mass  $\sim 10^{-4} M_\odot$ , amounts to  $10^{48} - 10^{49} \text{ erg}$  and can be released in nuclear explosions caused by mixing of matter of the upper crust resulting in transfer of super-heavy nuclei to the regions of lower density where they become unstable. During the lifetime of the layer ( $\sim 10^4 \text{ yr}$ ) this amount of energy is sufficient to provide both the X-ray luminosity of AXPs and more than 1000 recurring gamma-ray bursts observed from SGRs. The spin-down power of the neutron star in the initial version of this scenario (see [13]) was associated with the outflow of relativistic wind generated due to nuclear explosions on its surface.

The second approach is based on the scenario of fall-back accretion onto a young neutron star which can occur under certain conditions soon after the supernova explosion [14, 15, 16, 17, 18]. In this case the star turns out to be surrounded by the residual dense gaseous disk from which the star accretes material onto its surface [2]. Numerical simulations presented in the papers [19, 20], show that over the time span of  $\sim 10^4 - 10^5$  years the rate of mass accretion from the fossil disk onto the stellar surface remains at the level of  $\dot{M} \sim 10^{13} - 10^{15} \text{ g s}^{-1}$ , sufficient to provide X-ray luminosity of AXPs and SGRs. Analyzing X-ray spectra of these sources, Trümper et al. [21, 22] have shown that they can be well explained within the model of disk accretion onto a neutron star with the dipole magnetic moment  $\mu = (1/2)B_*R_{\text{ns}}^3$  in the range  $10^{30} - 10^{31} \text{ G cm}^3$ , where  $B_*$  is the surface magnetic field of the neutron star and  $R_{\text{ns}}$  is its radius. This makes it possible

to consider AXPs and SGRs as a subclass of accreting pulsars in which parameters of the isolated neutron star are close to their canonical values.

Scenarios constructed in the frame of the second approach propose the simplest and the most consistent description of the basic characteristics of X-ray emission from AXPs and SGRs. At the same time they reveal their incompleteness leaving unanswered the question about the nature of flaring activity of these objects. It is customary to avoid this problem by making additional assumptions about very strong small-scale magnetic field on the accreting star surface which could undergo flaring dissipation causing flaring activity of the pulsar in gamma-rays [21, 22].

In this paper we show that the age of such an accreting “quasi-magnetar” must significantly exceed that of anomalous X-ray pulsars estimated through their spin-down rates and the ages of associated supernova remnants. As alternative we suggest a scenario in which flaring activity of AXPs and SGRs is explained by nuclear explosions resulting from the release of energy stored in the non-equilibrium layer. We start discussion of this hypothesis analyzing the structure of the fossil disk forming in the process of fall-back accretion (see Section 2). We come to the conclusion that after the supernova explosion a neutron star turns out to be surrounded by a residual magnetic slab of low angular momentum for a wide range of its basic parameters. In this case, the X-ray luminosity and spin-down rate of AXPs and SGRs can be described within the model of accretion from the slab provided the dipole magnetic moment of the star is  $\sim 10^{29} - 10^{31} \text{ G cm}^3$ . The star with the initial (at the time of birth) spin period of  $P_0 \geq 65 \text{ ms}$  reaches this stage at a relatively young age ( $10^3 - 10^4$  years), beginning its evolution in the propeller state. It transits to the accretor state as soon as its rotation decelerates to the period in the range  $2 - 12 \text{ s}$ . Mass accretion onto the surface of the star may be one of the main factors contributing to the mixing of matter in its outer crust leading to release of nuclear energy stored in the non-equilibrium layer (Section 3). The amount of this energy is sufficient for generation of  $\sim 200$  giant gamma-ray bursts occurring at an average recurrence interval of about 40 years.

Long spin periods and strong magnetic fields have been until recently believed to be the exclusive signs of magnetars and main indicators allowing to differentiate these objects from ordinary radio-pulsars. However, observational data cast serious doubt on the validity of this approach. Young et al. [23] reported the discovery of a long-period radio-pulsar with the period of 8.5 seconds. Besides, the magnetic fields of a number of neutron stars manifesting themselves as ordinary radio-pulsars reach values typical for hypothetical magnetars. In particular, the magnetic field strength of the neutron star PSR J1119-6127, rotating with the period of  $P_s = 0.407 \text{ s}$ , is as high as  $B = 4.1 \times 10^{13} \text{ G}$ . The magnetic field  $B = 5.5 \times 10^{13} \text{ G}$  was obtained for the radio-pulsar PSR J1814-1744, spinning with the period  $P_s = 3.975 \text{ s}$  [24]. Strong magnetic fields have been detected in the radio-pulsars (see [25]) PSR J1847-013 ( $P_s = 6.7 \text{ s}$ ,  $B = 9.4 \times 10^{13} \text{ G}$ ) and PSR J1718-37 ( $P_s = 3.4 \text{ s}$ ,  $B = 7.4 \times 10^{13} \text{ G}$ ). From the other hand, the magnetic field strength of the neutron star SGR 0418+5729, exhibiting flaring activity which unambiguously allows to classify this star as an object of AXP/SGR subclass, is as weak as  $B = 7.5 \times 10^{12} \text{ G}$ , [26], which is quite typical for radio-pulsars. This means that strong magnetic field does not constitute the necessary condition of the star’s flaring activity in the gamma-rays and cannot serve as explicit criterion for its assigning to the subclass of AXPs/SGRs.

The main parameter determining the difference between SGRs and radio-pulsars within the model of flaring activity associated with non-equilibrium layer is the mass of a neutron star [27]. The mass of a non-equilibrium layer and the energy stored there increases as the mass of the neutron star decreases so that beginning from a certain value of the neutron star mass (unknown so far) the non-equilibrium layer starts to exhibit flaring activity up to an appearance of giant flares. This allows to suggest a hypothesis that SGR-type activity characterizes low-mass neutron stars with massive non-equilibrium layers [27]. Basic conclusions of our scenario are briefly summarized in Section 4.

## 2. ISOLATED ACCRETING PULSARS

Modeling of supernova explosion (see, e.g., [28, 29]) has shown that at the time of birth a neutron star is embedded in the dense gaseous media which can essentially influence its further evolution. In particular, under these conditions the star can switch into the ejector state only provided the pressure of relativistic wind being ejected from its magnetosphere,  $p_{\text{rw}}(r) = W_{\text{ej}}/4\pi r^2 c$ , exceeds the ram pressure,  $p_{\text{ram}}(r) = \rho(r)v_{\text{ff}}^2(r)$ , of the gas, located at the distance  $r$ , surpassing the light cylinder radius,  $r_{\text{lc}} = c/\omega_s$ . Here  $\rho$  and  $v_{\text{ff}} = (2GM_{\text{ns}}/r)^{1/2}$  are the density and free-fall velocity of the gas, surrounding the neutron star of the mass  $M_{\text{ns}}$ .  $W_{\text{ej}} = f_m \mu^2 \omega_s^4 / c^3$  is the spin-down power of the neutron star expected within a radio-pulsar model.  $\mu$  and  $\omega_s = 2\pi/P_s$  are the dipole magnetic moment and the angular velocity of the star, rotating at the period  $P_s$ , and  $f_m$  is the dimensionless parameter which in general case is limited as  $1 \leq f_m \leq 4$  (see [30, 31] and references therein). Combining these parameters, one finds that inequality  $p_{\text{rw}}(r_{\text{lc}}) > p_{\text{ram}}(r_{\text{lc}})$  is fulfilled if the initial spin period of the star,  $P_0$ , satisfies the condition  $P_0 < P_{\text{cr}}$ , where

$$P_{\text{cr}} \simeq 0.24 f_m^{2/7} \mu_{30}^{4/7} \mathfrak{M}_{15}^{-2/7} m^{-1/7} \text{ s}. \quad (1)$$

Here  $\mu_{30}$  and  $m$  are the initial dipole magnetic moment and the mass of the neutron star in units  $10^{30} \text{ G cm}^3$  and  $1.4 M_{\odot}$ , and  $\mathfrak{M}_{15} = \mathfrak{M}/10^{15} \text{ g s}^{-1}$ , where  $\mathfrak{M} = 4\pi r^2 \rho(r)v_{\text{ff}}(r)$  is the mass transfer rate towards the neutron star. The surrounding gas in this case is blown away by the relativistic wind of the star beyond its Bondi radius,  $r_G = 2GM_{\text{ns}}/v_{\text{rel}}^2$ , and at early stages of its evolution the star displays itself as a radio-pulsar. Here  $v_{\text{rel}}$  is the velocity of the star in the reference frame of the surrounding gas.

Rapid rotation is one of the necessary conditions of magnetars formation, which are expected to have an initial spin period not exceeding a few milliseconds [9]. Under these conditions, the star begins its evolution in the ejector state for all excepted values of the parameter  $\mathfrak{M}$ , given in the paper [18]. Its spin period in this case gradually increases according to the canonical radio-pulsar model and reaches the critical value at which the star switches to the propeller state on the time-scale [32]

$$\tau_{\text{ej}} \simeq 10^6 f_m^{-1/2} I_{45} \mu_{30}^{-1} \mathfrak{M}_{15}^{-1/2} v_8^{-1/2} \text{ yr}, \quad (2)$$

where  $I_{45} = I/10^{45} \text{ g cm}^2$  is the moment of inertia of the neutron star and  $v_8 = v_{\text{rel}}/10^8 \text{ cm s}^{-1}$ . Thus, a star with initial spin period  $P_0 < P_{\text{cr}}$  can switch to

the accretor state (which succeeds the propeller state) on the timescale comparable with the age of AXPs and SGRs (e.g.  $\leq 10^4$  yr) only provided  $\mu \geq 10^{32} \text{ G cm}^3$ . In this light, a possibility to form an accreting “quasi-magnetar” (that is a neutron star whose strong small-scale surface magnetic field does not make significant contribution in its dipole magnetic moment which is close to its canonical value  $\mu \sim 10^{30} \text{ G cm}^3$ , [22]) looks rather doubtful, since the evolution time of these stars in the ejector state exceeds the characteristic decay time of supercritical magnetic field estimated in [33].

Statistical analysis of the observed radio-pulsar characteristics [34, 35, 36, 37] shows evidence that at the time of birth the periods of these objects are as a rule in excess of a few tens of milliseconds. From a theoretical point of view, this conclusion can be directly obtained from the model of magnetorotational explosion of core-collapse supernovae [38, 28]. The condition for a star to switch to the ejector state in this case can be written in a form  $\dot{\mathfrak{M}} < \dot{\mathfrak{M}}_{\text{cr}}$ , where

$$\dot{\mathfrak{M}}_{\text{cr}} \simeq 2 \times 10^{16} f_{\text{m}}^{7/2} \mu_{30}^2 m^{-1/2} \left( \frac{P_0}{0.1 \text{ s}} \right)^{-7/2} \text{ g s}^{-1} \quad (3)$$

is a solution of equation  $P_0 = P_{\text{cr}}(\dot{\mathfrak{M}})$ . Otherwise, a scenario of fall-back accretion is realized, in which the gas captured by the neutron star after its birth forms an accretion flow approaching the star to the distance smaller than its light cylinder radius and directly interacting with stellar magnetic field.

## 2.1. Accretion flow structure

Modeling of the fall-back accretion [18] indicates that the matter, captured by the neutron star after the supernova explosion, possesses a relatively low angular momentum (its angular velocity does not exceed that of the progenitor star and is significantly smaller than Keplerian velocity) and its accretion onto the star takes place in a quasi-spherical regime. The duration of this phase is limited, however, by the free-fall time of matter at the Bondi radius,  $t_{\text{ff}}(r_{\text{G}}) \sim (r_{\text{G}}^3/2GM_{\text{ns}})^{1/2}$ , which for the parameters of interest ( $r_{\text{G}} \leq 10^{11} \text{ cm}$ ) is negligibly small comparing to the age of AXPs. That is why, constructing the accretion scenario for these objects is impossible without an additional assumption that over the time span  $t < t_{\text{ff}}(r_{\text{G}})$  the initial quasi-spherical flow is transformed into a residual disk, in which the characteristic time of radial motion is at least 10 000 years. One of indirect evidences of feasibility of this suggestion is provided by observation of planetary system surrounding the pulsar PSR 1257+12 [39, 40, 41].

Modeling of a residual disk has been until recently performed in terms of Keplerian accretion disk with initial mass  $\sim 10^{-5} M_{\odot}$  [16]. One of possible causes of its formation is an effective turbulization of matter, captured by the neutron star, due to propagation of reverse shock wave [17, 18]. Studies [19] have shown that such disk can donate matter to the neutron star at the rate  $10^{14} - 10^{16} \text{ g s}^{-1}$  on the timescale  $10^4 - 10^5$  years, which is sufficient to explain X-ray luminosity of AXPs and SGRs [20]. At the same time, the scenario of accretion through the Keplerian fossil disk encounters some difficulties in interpretation of a regular spin-down of these pulsars which occurs nowadays at a

rather high rate. Such behavior of a pulsar means that the spin period of a neutron star is significantly smaller than its equilibrium period [42]. However, estimates presented in [43, 20], suggest otherwise. Equilibrium period of the neutron star with the dipole magnetic moment of  $10^{30} \text{ G cm}^3$ , accreting material from the Keplerian disk at the rate  $\sim 10^{15} \text{ g s}^{-1}$ , is close to the range of observed periods of these pulsars. Moreover, the Alfvén radius of a neutron star,  $r_A = (\mu^2 / \dot{M} \sqrt{2GM_{\text{ns}}})^{2/7}$ , under these conditions exceeds the corotation radius of AXPs and SGRs by a factor of 2 and turns out to be an order of magnitude greater than the magnetospheric radius estimated through the temperature measurements of the black-body component in the X-ray spectra of these sources. These inconsistencies indicate that either X-ray emission from AXPs and SGRs is not accretion-driven or the accretion flow structure deviates from the Keplerian disk.

As first shown in [44, 45], the structure of accretion flow onto a gravitating compact object can essentially differ from the Keplerian disk if infalling matter possesses sufficiently strong magnetic field  $B_f$ . Rapid magnetic field amplification in the quasi-spherical flow leads to its deceleration and further transformation into a magnetic disk-like envelope (magnetic slab) with low angular momentum. This change of the flow structure occurs at the Shvartsman radius [46]

$$R_{\text{sh}} = \beta_0^{-2/3} \left( \frac{c_s(r_G)}{v_{\text{rel}}} \right)^{4/3} r_G, \quad (4)$$

at which the magnetic pressure in the accretion flow,  $E_m = B_f^2(r)/8\pi \propto r^{-4}$ , reaches its ram pressure,  $E_{\text{ram}} = \rho(r)v_{\text{ff}}^2(r) \propto r^{-5/2}$ . Here  $\beta_0 = E_{\text{th}}(r_G)/E_m(r_G)$ ,  $E_{\text{th}}(r) = \rho(r)c_s^2(r)$  is the thermal pressure and  $c_s$  is the sound speed in the accretion flow.

Material of the magnetic slab retains equilibrium by intrinsic magnetic field of the accretion flow and moves towards the compact star with velocity  $v_r \sim r/\tau_m$  due to dissipation of this field occurring on the timescale  $\tau_m$ , significantly exceeding the free-fall time [44, 45]. Basic conclusions of this scenario were confirmed by numerical simulations of spherical accretion of magnetized plasma onto a black hole [47].

Magnetic accretion onto a neutron star have been recently discussed in [49, 48, 32]. These studies have shown that transformation of the quasi-spherical flow into a magnetic slab takes place if the Shvartsman radius exceeds a canonical Alfvén radius. This condition is valid if  $v_{\text{rel}} < v_{\text{ma}}$ , where

$$v_{\text{ma}} \simeq 1155 \beta_0^{-1/5} \mu_{30}^{-6/35} \dot{M}_{15}^{3/35} m^{12/35} \left( \frac{c_s(r_G)}{100 \text{ km s}^{-1}} \right)^{2/5} \text{ km s}^{-1}. \quad (5)$$

Interaction between the slab and the dipole magnetic field of the neutron star results in formation of the magnetosphere, whose minimum radius is estimated as (see Eq. 12 in [50])

$$r_{\text{ma}} = \left( \frac{cm_p^2}{16\sqrt{2}ek_B} \right)^{2/13} \frac{\alpha^{2/13} \mu^{6/13} (GM_{\text{ns}})^{1/13}}{T_0^{2/13} \dot{M}^{4/13}}, \quad (6)$$

where  $m_p$  and  $k_B$  are the proton mass and the Boltzmann constant, and  $T_0$  is the gas temperature at the inner radius of the slab in the region of its interaction with magnetic

field of the neutron star. A dimensionless parameter  $\alpha = D_{\text{eff}}/D_B$ , coming into this expression, determines the ratio of the effective coefficient of the accretion flow diffusion into the magnetic field of the star at its magnetospheric boundary,  $D_{\text{eff}}$ , to the Bohm diffusion coefficient  $D_B = ckT/16eB$  [51], and its value, following Gosling et al. [52], ranges within 0.1 – 0.25. Plasma penetrates into the stellar magnetic field and reaches its surface in the magnetic poles regions flowing along the field lines. The radius of the base of the accretion column arising due to this process in a dipole magnetospheric field approximation can be estimated by an expression  $a_p \sim R_{\text{ns}} (R_{\text{ns}}/r_{\text{ma}})^{1/2}$  [42].

Spin evolution of the neutron star in the magnetic accretion scenario strongly depends on the angular velocity of matter at the inner radius of the slab. Its value in general case is limited by inequality  $0 \leq \Omega_{\text{sl}} < \omega_k$ , where  $\omega_k(r) = (GM_{\text{ns}}/r^3)^{1/2}$  is the Keplerian angular velocity. Spindown can be observed provided  $\Omega_{\text{sl}}(r_m) < \omega_s$  [53]. Absolute value of the spindown torque applied to the neutron star from the magnetic slab under this condition is evaluated according to expression (see Eq. 8 from [50])

$$|K_{\text{sd}}^{(\text{sl})}| = \frac{k_m \mu^2}{(r_{\text{ma}} r_{\text{cor}})^{3/2}} \left( 1 - \frac{\Omega_{\text{sl}}(r_m)}{\omega_s} \right), \quad (7)$$

where  $r_{\text{cor}} = (GM_{\text{ns}}/\omega_s^2)^{1/3}$  is the corotation radius of the neutron star and  $k_m$  is a dimensionless parameter of the order of unity.

## 2.2. Parameters of the sources

Parameters of AXPs and the best studied SGRs are collected in Tables 1 and 2. We consider a situation in which these objects are isolated neutron stars undergoing mass accretion onto their surface from the magnetic slab. The magnetospheric radius of a neutron star in this case is denoted by expression (6). Solving inequality  $r_{\text{ma}} \leq r_{\text{cor}}$  for  $\mu$ , we find that centrifugal barrier at the magnetospheric boundary would not prevent plasma from reaching the stellar surface provided  $\mu \leq \mu_{\text{max}}$ , where

$$\mu_{\text{max}} \simeq 10^{30} \text{ G cm}^3 \alpha_{0.1}^{-1} T_6^{1/3} m^{-1/9} L_{34}^{2/3} R_6^{2/3} P_s^{13/9}, \quad (8)$$

$R_6 = R_{\text{ns}}/10^6 \text{ cm}$ ,  $\alpha_{0.1} = \alpha/0.1$  and  $P_s$  is the pulsar spin periods in seconds. This condition determines the maximum possible value of the dipole magnetic moment of the neutron star in the scenario under consideration. The lower limit to the dipole magnetic moment of the neutron star undergoing spindown at the rate  $\dot{\nu}_{\text{sd}}$ , can be retrieved solving inequality  $|K_{\text{sd}}| \geq 2\pi I |\dot{\nu}_{\text{sd}}|$ . Taking  $|K_{\text{sd}}| = |K_{\text{sd}}^{(\text{sl})}|$  (see formula 7) and solving this inequality for  $\mu$ , we find  $\mu \geq \mu_{\text{min}}$ , where

$$\begin{aligned} \mu_{\text{min}} \simeq & 7 \times 10^{28} \text{ G cm}^3 \times P_s^{13/17} L_{34}^{6/17} \dot{\nu}_{-12}^{13/17} \times \\ & \times k_m^{-13/17} \alpha_{0.1}^{9/17} I_{45}^{13/17} m^{14/17} T_6^{3/17} R_6^{2/3}. \end{aligned} \quad (9)$$

The magnetic field strength,  $B_* = 2\mu_{\text{min}}/R_{\text{ns}}^3$ , on the surface of AXPs and SGRs as well as the magnetospheric radius,  $r_{\text{ma}}(B_*)$ , and the radius of the accretion column base,

**TABLE 1.** Anomalous X-ray Pulsars\*

Name**	$P_s$ , s	$\dot{P}$ , $10^{-11}$ s/s	$\tau$ , $10^3$ yr	$L_X$ , $10^{34}$ erg/s	$T_{bb}$ , keV	$d$ , kpc
1E 1547.0-5408	2.07	4.7	0.7	0.08	0.43	4.5
CXOU J174505.7-381031	3.83	6.4	0.95	6.0	0.38	13.2
PSR J1622-4950	4.33	1.7	4.0	0.063	0.4	9
XTE J1810-197	5.54	0.8	11	3.9	0.2	3.5
1E 1048.1-5937	6.45	2.3	4.5	0.6	0.51	2.7
1E 2259+586	6.98	0.048	230	2.2	0.4	3.2
CXOU J010043.1-721134	8.02	1.88	6.8	6.1	0.38	60
4U 0142+61	8.69	0.2	70	11	0.4	3.6
CXO J164710.2-455216	10.61	0.07	230	0.3	0.5	4
1RXS J170849.0-400910	11.0	1.9	9.1	5.9	0.45	3.8
1E J1841-045	11.8	3.93	4.8	19	0.45	8.5

\* Data from electronic catalogue “McGill SGR/AXP Online Catalog”

<http://www.physics.mcgill.ca/pulsar/magnetar/main.html>

\*\* Parameters presented in the table:  $P_s$  is the spin period of a pulsar and  $\dot{P} = dP_s/dt$  is its derivative  $\tau = P_s/2\dot{P}$ ,  $L_X$  is the X-ray luminosity,  $T_{BB}$  is the temperature of blackbody component, and  $d$  is the distance to an object

**TABLE 2.** Soft Gamma-Ray Repeaters\*

Name**	$P_s$ , s	$\dot{P}$ , $10^{-11}$ s/s	$\tau$ , $10^3$ yr	$L_X$ , $10^{34}$ erg/s	$T_{bb}$ , keV	$d$ , kpc
SGR 1627-41	2.6	1.9	2.2	1.0	0.5	11
SGR 1900+14	5.2	9.2	0.9	9.0	0.43	12-15
SGR 1806-20	7.6	75	0.16	16	0.6	8.7
SGR 0526-66	8.05	3.8	2.2	14	0.53	50

\* Data from electronic catalogue “McGill SGR/AXP Online Catalog”

<http://www.physics.mcgill.ca/pulsar/magnetar/main.html>

\*\* Parameters are the same as in Table 1

$a_p \simeq [R_{ns}^3/r_{ma}(B_*)]^{1/2}$ , together with the blackbody temperature,  $T_{bb}$ , calculated within the magnetic accretion approach, are presented in Table 3. Parameters of the objects, displayed in this Table, favor accretion nature of their X-ray radiation. Presented values of the magnetic field strength on the surface of these neutron stars are in a good agreement with the observational data on their X-ray spectra. The magnetospheric radii of these stars within our scenario do not exceed their corotation radii, and expected spindown rates are in accordance with the observed values. Finally, the expected temperatures of blackbody radiation emitted at the base of the accretion column, are also close to their observational estimates. Somewhat larger value of this parameter estimated for a number of sources can be connected with an effect of additional heating of the neutron star surface by the hard radiation generated due to comptonization of soft photons on the electrons of accretion flow.



**TABLE 3.** Parameters of AXPs and SGRs within the model of magnetic accretion\*

Name	$P_s$ , s	$ \dot{V}_{sd} $ , $10^{-12}$ $\text{Hz s}^{-1}$	$L_X$ , $10^{34}$ $\text{erg s}^{-1}$	$B_*$ , $10^{12}$ G	$r_{\text{cor}}$ , $10^8$ cm	$r_{\text{ma}}$ , $10^8$ cm	$a_p$ , $10^5$ cm	$T_{\text{bb}}$ , keV
SGR 1627-41	2.6	2.8	0.25	3.9	3.2	1.2	0.9	0.5
SGR 1900+14	5.2	3.4	9.0	2.7	5.2	1.0	1.0	1.1
SGR 1806-20	7.6	13	16	12	6.6	1.7	0.8	1.4
SGR 0526-66	8.05	0.59	14	1.2	6.9	0.6	1.3	1.1
1E 1547.0-5408	2.07	11	0.08	0.63	2.8	2.1	0.7	0.4
J174505.7-381031	3.83	4.4	6.0	2.3	4.2	1.0	1.0	0.98
J1622-4950	4.33	0.9	0.063	1.5	4.6	1.2	0.9	0.33
J1810-197	5.54	0.26	3.9	0.3	5.4	0.46	1.5	0.73
1E 1048.1-5937	6.45	0.55	0.6	0.31	5.95	0.83	1.1	0.53
1E 2259+586	6.98	0.01	2.2	0.024	6.3	0.17	2.4	0.49
J010043.1-721134	8.02	0.29	6.1	0.51	6.9	0.51	1.4	0.83
4U 0142+61	8.69	0.03	11	0.11	7.26	0.21	2.2	0.77
J164710.2-455216	10.61	0.006	0.3	0.011	8.3	0.22	2.1	0.32
J170849.0-400910	11.0	0.16	5.9	0.4	8.5	0.46	1.5	0.81
1E J1841-045	11.8	0.28	19	0.99	8.9	0.49	1.4	1.1

\*  $|\dot{V}_{sd}|$  is the observed spindown rate of a pulsar,

$B_*$  is the surface magnetic field  $B_* = (1/2)\mu_{\text{min}}R_{\text{ns}}^3$  (see Eq. 9)

$a_p$  is the radius of the accretion column base and

$T_{\text{bb}}$  is the effective blackbody temperature  $T = \left( \frac{L_X}{2\pi a_p^2 \sigma_{\text{SB}}} \right)^{1/4}$

### 2.3. Age and period clustering

As shown above, the life time of a neutron star in the ejector state under conditions of interest significantly exceeds the age of AXPs and SGRs, evaluated from their spindown rates and the age of associated supernova remnants. However, a much higher spindown rate of a neutron star is expected if it starts its evolution in the propeller state. This situation can be realized in case the initial mass accretion rate towards a neutron star,  $\dot{\mathfrak{M}}_0$ , satisfies inequality  $\dot{\mathfrak{M}}_0 \geq \dot{\mathfrak{M}}_{\text{cr}}$  (see expression 3). The pulsar age,  $\tau$ , in this case is limited solely by the spindown time of a neutron star in the propeller state,  $\tau \geq \tau_{\text{pr}} = \pi I / P_0 K_{\text{sd}}^{\text{pr}}$ , which for the case of maximum possible value of spindown torque,  $K_{\text{sd}}^{\text{pr}} = \dot{\mathfrak{M}} \omega_s r_m^2$ , can be estimated as follows:

$$\tau_{\text{pr}} = \frac{I}{2\dot{\mathfrak{M}} r_m^2}. \quad (10)$$

Taking into account that the magnetospheric radius of a neutron star in the propeller state is limited as  $r_m \geq r_{\text{cor}}$ , we find

$$\tau_{\text{pr}} \simeq 1870 I_{45} \left( \frac{\dot{\mathfrak{M}}_0}{10^{17} \text{ g s}^{-1}} \right)^{-1} \left( \frac{r_{\text{cor}}}{3 \times 10^8 \text{ cm}} \right)^{-2} \text{ yr.} \quad (11)$$

Thus, in the scenario under consideration, AXPs and SGRs are relatively young neutron stars. Their period is likely to correspond to the period of transition of a neutron star from propeller to accretor state [20]. Observed period clustering in the frame of this hypothesis indicates that the magnetospheric radius of these neutron stars in the propeller state,  $r_m^{(\text{pr})}$ , was in the range  $(2.8 - 8.9) \times 10^8 \text{ cm}$  and, hence, significantly exceeded that in the present epoch (see Table 3). This conclusion does not contradict our results presented in the previous sections. It rather points at the circumstance that the diffusion coefficient at the magnetospheric boundary of a star in the propeller state significantly exceeds the Bohm diffusion coefficient. This can be connected with plasma turbulization [45] by a shock wave generated at the magnetospheric boundary of a star in the supersonic propeller state. As the diffusion coefficient grows, the radius of stellar magnetosphere increases up to the Alfvén radius,  $r_A$ , whose value for the parameters of interest ( $\dot{\mathfrak{M}} \sim 10^{16} - 10^{17} \text{ g s}^{-1}$  and  $B \sim 10^{12} - 10^{13} \text{ G}$ ) corresponds to the above mentioned interval for  $r_m^{(\text{pr})}$ .

### 3. FLARING ACTIVITY OF AXPS AND SGRS

Findings of the previous sections make it possible to explain high X-ray luminosity and rapid spindown of AXPs and SGRs within the scenario for accretion of matter from the fossil magnetic slab onto the surface of a young neutron star with basic parameters close to canonical. This approach exclude a possibility to describe the pulsar activity in gamma-rays in terms of flaring dissipation of its magnetic field. The model involving non-stationary accretion turn out not to be effective because of extremely high (super-Eddington) luminosity of the sources during the flares. The latter circumstance unambiguously indicates that the source of energy released in the course of flares is located in the star itself and, hence, is connected with peculiarities of its internal structure.

#### 3.1. Energy of non-equilibrium layer

A possibility to form a considerable reservoir of energy in the crust of a young neutron star was first pointed out in the paper by Bisnovatyi-Kogan & Chechetkin [11]. They have shown that a non-equilibrium layer of super-heavy nuclei with a large energy excess relative to the equilibrium state can be generated in the envelope of a young neutron star. This non-equilibrium layer is forming at the interface between the inner and outer crust of the neutron star and at the densities  $\rho_{\text{nel}} \sim 10^{10} - 10^{12} \text{ g cm}^{-3}$  remains in quasi-equilibrium state. The initial mass of the layer is  $M_{\text{nel}} \sim 10^{-4} M_{\odot}$  [12], and its life time

in the absence of instabilities can be infinitely long. The total energy accumulated in the non-equilibrium layer can be as large as  $\sim 10^{49}$  erg (see Eqs. 5.6–5.9 in [13]).

A release of *free* energy stored in the non-equilibrium layer can occur as mixing of matter in the neutron star crust proceeds and heavy nuclei from the non-equilibrium layer reach the outer layers of the star in which the density of material is  $< 10^{10}$  g cm $^{-3}$ . Under these conditions super-heavy nuclei become unstable to  $\beta$ -decay which initiate the process of nuclei fission and  $\alpha$ -decays, leading to chain reaction and, finally, to the nuclear explosion (see [54] for detailed discussion). Duration of the energy release process in this case is determined by the characteristic time of  $\beta$ -decay (the slowest process in this chain), which for parameters of interest is  $\tau_\beta \sim 10^{-4} - 50$  s (see Eq. 7.5 in [13]). This covers the range of emission times of gamma-ray bursts observed from SGRs, and at the same time the spectrum of primary radiation generated in nuclear explosion ranges in the energy interval 0.002 – 3 MeV. The energy efficiency of neutrons transmutation in a nucleus amounts to 1% of their rest energy, and  $\sim 0.1\%$  of the rest energy of super-heavy nuclei can be released in the process of fission. Taking the value of efficiency parameter for the mixture of these components as  $\zeta \sim 3 \times 10^{-3}$ , we find that the mass on non-equilibrium matter, necessary for appearance of gamma-burst with the energy  $\varepsilon_\gamma$  in the frame of nuclear explosion scenario can be evaluated as:

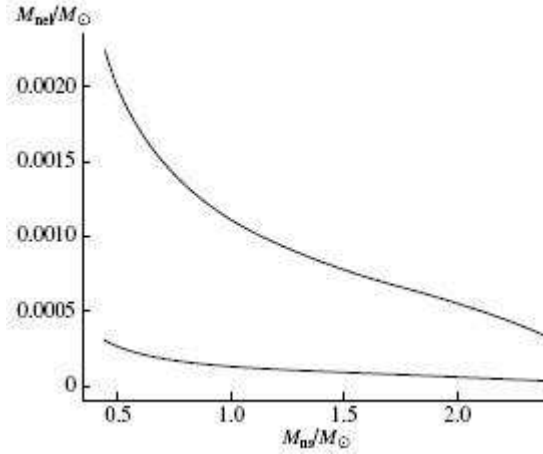
$$M_\gamma \simeq 4 \times 10^{26} \left( \frac{\zeta}{0.003} \right)^{-1} \left( \frac{\varepsilon_\gamma}{10^{45} \text{ erg}} \right) \text{ g}. \quad (12)$$

Thus, the energy accumulated in the non-equilibrium layer of a young neutron star proves to be sufficient for  $\sim 250$  giant ( $\sim 10^{45}$  erg) gamma-bursts, which can occur with average recurrence time of  $\sim 40$  years over a time span of  $\sim 10^4$  years.

### 3.2. Trigger of the flare

According to results of calculations presented in [27], the mass of the non-equilibrium layer, forming in the crust of light neutron stars, exceeds that in more massive stars (Fig. 1). This allows to choose neutron stars of moderate mass as the most probable candidates for SGRs and implies possible distinction of supernova remnants associated with the birth of these objects. The latter is in accordance with results by Marsden et al. [55] about relative compactness and higher density of supernova remnants identified with AXPs and SGRs. They have noted that observational appearance of these nebulosities may speak in favor of a relatively low energy of supernova explosion that is typical for the birth of low-mass neutron stars.

Analyzing the galactic population of neutron stars one can conclude that the youth of these objects is not a sufficient condition for realization of AXP and SGR phenomenon. Only these 23 objects among a large number of neutron stars with parameters satisfying the above mentioned criteria demonstrate flaring activity in gamma-rays. This implies that energy release from the non-equilibrium layer can neither proceed spontaneously nor be exclusively connected with peculiarities of structure evolution of the star itself (in particular, starquakes, volcanic activity and tensions arising in the stellar crust in the



**FIGURE 1.** Dependence of mass of the non-equilibrium layer on the neutron star mass. Lines show the top and bottom boundaries of the layer mass which is counted from the stellar surface. The state equation of equilibrium matter has been used in constructing the model of neutron star with boundaries of the layer setting by densities. Using the state equation accounting for non-equilibrium will increase the mass of the layer but should not essentially change the values given in the Figure.

presence of phase transition “liquid-gas”). The flare seems to be triggered by the action of external factors on the star, one of which may be accretion of matter onto its surface.

### 3.3. Possible model of a low-mass neutron star formation

The birth of a low-mass neutron star should be a rather rare event, since a fraction of AXP/SGRs among currently known neutron stars is as low as one percent (see, e.g. [1, 56]). Detection of binary pulsars in systems with neutron stars enabled accurate determination of their masses. For instance, the observations of a binary pulsar system J 1518+4904 revealed with probability 95.4% that the masses of components are  $m_p = 0.72^{+0.51}_{-0.58} M_\odot$  and  $m_e = 2.00^{+0.58}_{-0.51} M_\odot$  [57].

The most accurate measurements of neutron stars masses were carried out for two close binaries consisting of neutron stars, in which effects of general relativity are the most clearly displayed. In one of them, containing the first binary pulsar discovered, the mass of the visible recycled pulsar is  $1.4424 M_\odot$ , while the mass of its invisible companion is  $1.386 M_\odot$  [58]. In another double pulsar system the mass of the recycled pulsar is  $1.3381 M_\odot$ , and the mass of the young “normal” pulsar is  $1.2489 M_\odot$  [59]. As we can see from above, the mass of the recycled pulsar in both systems exceeds the mass of its companion which has not undergone mass accretion. In the process of disk accretion the recycled pulsar mass is increased by an amount which does not depend on the value of its initial period (exceeding  $\sim 0.2$  s) and is related to the final spin period of a pulsar  $P_{ms}$  (in milliseconds) as [60]

$$\Delta m = 0.22 M_{\odot} \frac{(M/M_{\odot})^{1/3}}{P_{ms}^{4/3}}. \quad (13)$$

A pulsar with a final mass of  $1.4 M_{\odot}$  and a recycled spin period of either 2 ms, 5 ms, 10 ms or 50 ms requires to accrete an amount of mass 0.1, 0.03, 0.01 and  $0.001 M_{\odot}$ , respectively. Thus, in double neutron stars systems with spin periods in excess of 23 ms (see, e.g. [61]), the amount of mass added to an accreting pulsar during recycling is insignificant.

Neutron stars are born in core-collapse supernova explosion. Collapse results from the loss of hydrodynamic stability at final stage of evolution of massive stars. The majority of neutron stars observed as radio-pulsars and X-ray sources are likely to be born in this process. We assume that single low-mass neutron stars, which are suggested to be SGRs, are formed through another, rarely realized channel. As example let us consider the evolution of a single star of moderate mass, which ends with loss of thermal stability of a star and off-center explosion of its degenerate core. The models with off-center explosion and collapsing core were discussed in [62] for supernovae of Type Ib. An outcome of this process must depend on the mass ratio between the iron core and the shell with He and C–O layers. The mass of collapsing remnant should be close to that of an iron core which can amount to  $0.4 - 0.6 M_{\odot}$ . When the whole star (core + shell) loses its hydrodynamic stability, the collapse starts, the temperature in He and C–O shells exceeds the critical value that gives rise to thermonuclear explosion leading to ejection of both shells. As a result of this process a low-mass neutron star can be born. It is necessary to note, however, that a definite answer to the question about a possibility to realize this scenario requires numerical simulations of stellar evolution and, in particular, of the explosion dynamics.

## 4. CONCLUSIONS

The basic conclusion of this paper is that it is not necessary to invoke the magnetar hypothesis in order to explain the spin evolution of AXPs and SGRs. Expected spindown rate of a neutron star accreting matter from a non-Keplerian magnetic slab corresponds to the observed value provided the magnetic field strength on its surface is in the range  $10^{10} - 10^{13}$  G. The blackbody temperature of the pulsar X-ray radiation evaluated within this approach is also close to the observed estimate that speaks in favor of feasibility of the proposed scenario.

Flaring activity of a neutron star in gamma-rays in the absence of super-strong magnetic field can be explained assuming an existence of energy reservoir located under its surface. As such we consider a non-equilibrium layer of super-heavy nuclei which is forming at early stages of a neutron star evolution. In the frame of this approach, AXPs and SGRs turn out to be relatively light neutron stars undergoing accretion of matter onto their surface which lead to development of instabilities in their crust and can trigger their flaring activity.

Formation of a low-mass neutron star could be connected with off-center nuclear explosion and induced collapse of the star central region in supernova explosion. Discov-

ery of neutron stars with masses close to one solar mass evidences that the mass of the remnant formed in the process of collapse and supernova explosion can be significantly smaller than the initial mass of the collapsing core. This is an indirect confirmation of possibility to form low-mass neutron stars.

## ACKNOWLEDGMENTS

The authors are grateful to S.O. Tarasov and N.G. Beskrovnaya for their help in this work. NRI acknowledges the support of the RAS Presidium Program N 21 “Non-stationary phenomena in the Universe”, RFBR under grant N 13-02-00077 and President Support Program for Leading Scientific Schools NSH-1625.2012.2. GSBK acknowledges the support of RFBR under grant 11- 02-00602, the RAS Program “Formation and evolution of stars and galaxies” and President Support Program for Leading Scientific Schools NSH-5440.2012.2.

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